Analysis of Mixing and Dynamics Associated with the Dissolution of Hurricane-Induced Cold Wakes

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LONG-TERM GOALS

The main objective of the research is to provide scientists with a clearer understanding of the relative importance of the physical mechanisms involved in the recovery of the ocean from a cold wake formation, and to provide additional value and insight to the observations already being undertaken by the ITOP program.

OBJECTIVES

Our approach is to take two ocean models (our version of CUPOM and HYCOM) that have been adapted for idealized simulations and conduct a series of experiments aimed at understanding the relative roles of the surface forcing, wave-induced mixing and other turbulent processes, and horizontal eddy actions at the mesoscale and submesoscale regimes in affecting the recovery of the ocean from the tropical cyclone. The comparisons of the two models will also provide information on the uncertainty of our results due to varying physical parameterizations of the models, and also provide insight into our further realistic model simulations with the POM model as compared to the work that other researchers are performing with HYCOM.

APPROACH

The approach is to use two high-resolution ocean models (a hybrid version of CUPOM, and HYCOM), and use idealized and realistic simulations of cold wakes and observations from the ITOP field campaign to investigate the restratification processes affecting cold wakes.

WORK COMPLETED

The CUPOM model has been successfully ported to WHOI (see Figure 2 for some sensitivity simulations). In addition, we have set up the model for use with realistic forcing conditions (which has required a blending of COAMPS winds and OAFlux surface variables, see Figure 1 for resulting hybrid forcing data). Our initial simulations were performed using temperature and salinity profiles from uCTD data obtained during the R/V Revelle cruise. However, these data, even at a fair distance

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from the eye of the storm, still evidenced the mixed layer temperature and salinity profiles associated with incidents of strong mixing – the mixed layer depths were already at 100 m. Thus, although we had mixing associated with the storms down to 100+m, little cooling occurred since no entrainment was happening. Thus we have had to work with the global HYCOM model simulations to use for our initial profiles (with ML depths closer to 50 m) rather than the observations. This has resulted in much improved model simulations.

Using this data, we have performed a number of one-dimensional simulations using the realistic forcing and initial stratification, and are currently working on the three-dimensional model simulations. Some results of the one-dimensional modeling are shown below, in comparison with turbulence measurements. We are currently working with L. St. Laurent and S. Jayne to add value to the turbulence measurements by focusing on the following key science questions in our models:

(1) What is the relative importance of key mixing mechanisms that are evident in enhanced levels of dissipation near the surface relative to deeper measurements (momentum/wave forcing, inertial oscillations, and heat loss)?

(2) Observations during ITOP clearly demonstrated the importance of multiple features driving restratification of the cold wake, and we will attempt to investigate the importance of the surface heat flux, submesoscale variability, and mesoscale shear in both idealized cold wake scenarios and those corresponding to the measurements during the ITOP field campaign.

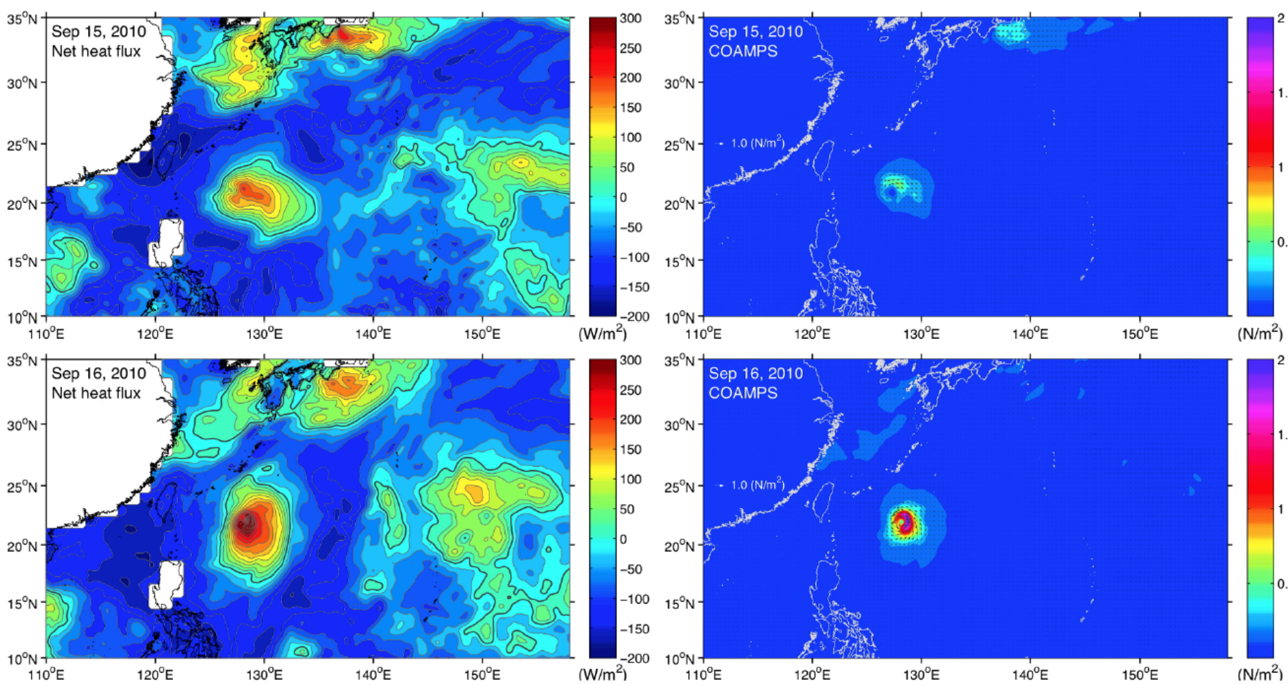

Figure 1. Representative forcing of net het flux and wind stress, hybrid values using COAMPS output and OAFlux (satellite and reanalysis) data.

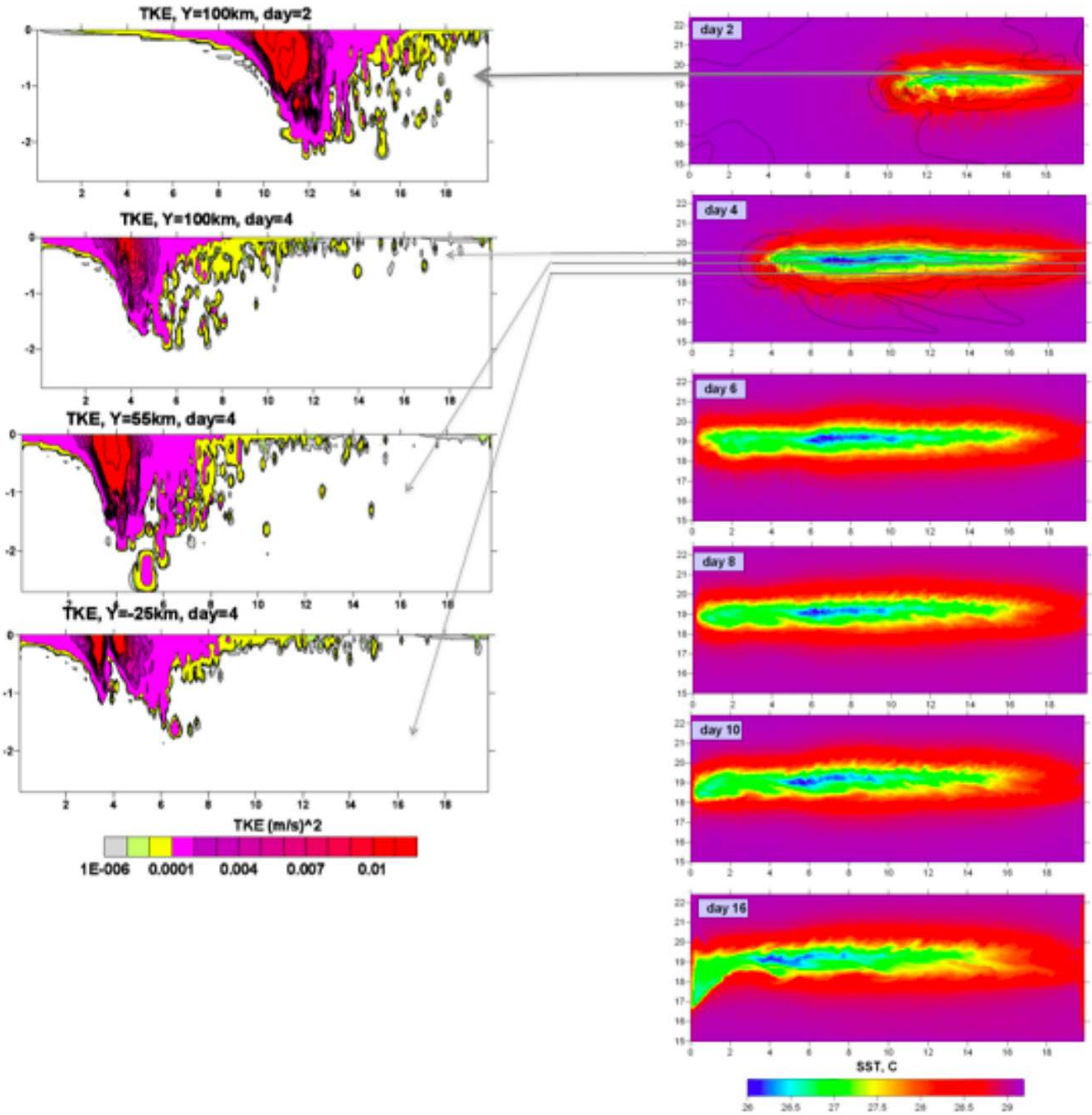

Figure 2. Model simulations of the sea surface temperature (right) and turbulence kinetic energy (left). Days noted are number of days after the hurricane enters the box at the eastern edge (taking roughly 5 days to pass through the box). The hurricane passes through the box at Y = 0 km (roughly 18.5^o), with the largest cooling taking place to the north of the eye.

RESULTS

Some sample results from the one-dimensional simulations in comparison with dissipation measurements have been performed and are described here. Figure 3 is one such set of temperature and dissipation variability from a point near the center of the storm and a location that was sampled in situ. Extended mixing to > 100 m is evident, and enhanced dissipation is seen near the surface and at depth for several days following the storm (more on this below).

Sea surface temperatures in this region drop by about 2.5^{o}C, but within 4 days of the passage of the storm the peak daily sea surface temperatures are comparable to prior the storms passage; however, the nocturnal SSTs and the ML temperatures do not recover to their pre-storm values (in part due to seasonally-reduced heat flux) within the next month.

For comparison with the observed dissipations (from L. St. Laurent) we have plotted the integrated dissipation as a function of time (Figure 4). Note that the observations do not have values from the upper 10 m, so here we plot the model simulations both with and without the upper 10 m. The extent to which mixing is occurring below 10 m during and immediately after the storm (September 18 here) is evidenced by the nearly consistent values between 0 – 100 m and 10 – 100 m; after the storm passes dissipation is decreased below 10m relative to the surface. Both profiles evidence a drop-off in dissipation of several orders of magnitude, with the drop-off being greater below the surface. The first observation at roughly 3 days past the storm is comparable in value to the model, with the model decrease larger (background mixing in the one-dimensional model is reduced compared to observations, as no internal waves and similar 3-D structures are evident). As with the observations, the model demonstrates an enhanced level of dissipation that is commensurate with the winds picking up again on September 24. The model presents a clear picture of a decrease in dissipation in the upper 100 m of over 4 orders of magnitude from the peak of the storm through the next 5 days, until winds pick up somewhat again, confirming the speculation that much of the dissipation that had occurred with the storm had been lost within the next two days (by again roughly 4 orders of magnitude).

We have begun experimenting with evaluating the role of heat fluxes vs. momentum fluxes in driving the dissipation results. For one set of simulations the heat flux during the three weeks just prior to, during, and after the typhoon was reduced by varying amounts; the results with a 50% reduction in heat flux loss (but solar radiation unchanged) is shown in Figure 5. The SST drop was roughly equivalent during the storm, but SSTs recovered to pre-storm values within 4 – 5 days. The integrated dissipation remained roughly equivalent. That the main contributor to the change in temperature of the upper ocean was the entrainment generated by momentum fluxes rather than convection is evident by contrasting the results when heat fluxes remain as observed but momentum fluxes are reduced by 50% (Figure 6). The SST drop is less than 2^{o}C, the mixed layer depth increase is substantially reduced, and the entire upper 50 m remains much warmer.

Our initial results thus highlight the role of momentum and entrainment towards enhancing mixing and sea surface temperature variability. It should be noted that including Langmuir circulation and an idealized wave field made little difference to the overall results outside of the very uppermost meters. The goals of the next year are to make realistic three-dimensional simulations; finish configuring and using the HYCOM model; and fully addressing the questions outlined above. Although here we have focused on the initial storm environment, in part due to comparison with observations, with the full three-dimensional model simulations we can include the effects of inertial oscillations, submesoscale variability, and enhanced shear in cold wake recovery. At least in the one-dimensional model simulations, the cold wake recovery itself depends mainly on the heat/momentum flux environment after the storm itself. Further simulations will explore this by removing the storm from the fluxes and evaluating the post-storm variability in comparison.

Initial simulation studies evidence the importance of submesoscale variability and such observed values as enhanced TKE and dissipation to the right (north) of the storm. These will be enhanced with more realistic ITOP forcings.

IMPACT/APPLICATIONS

ONR has a substantial investment in ITOP, and in the ITOP Cold wake cruises, to provide high-quality turbulence and other upper ocean measurements related to the development and recovery of the cold wakes. This work will greatly enhance the physical understanding that will come from that investment. It is anticipated that this understanding can directly benefit researchers using coupled atmosphere-ocean models to predict hurricane track and intensity, and can also be used to address the importance of hurricane-induced mixing for the global ocean thermohaline circulation and the global climate.

RELATED PROJECTS

Observations of Energy Dissipation in the Wake of a Western Pacific Typhoon, L. St. Laurent, PI.

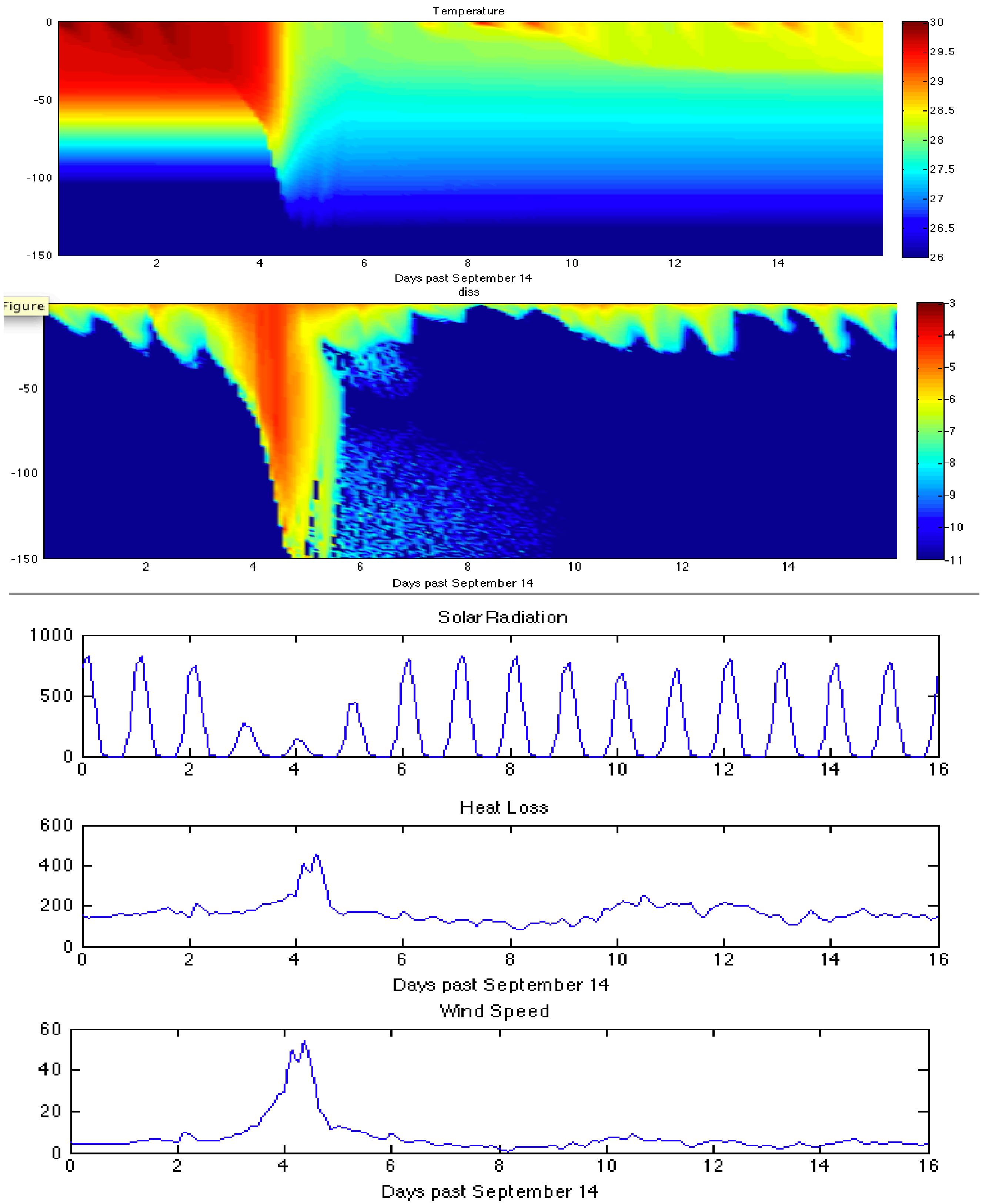

Figure 3. Model simulations of the temperature (top) and dissipation (bottom). Days noted are number of days after September 14. Also shown for comparison are the heat fluxes and winds during this time period.

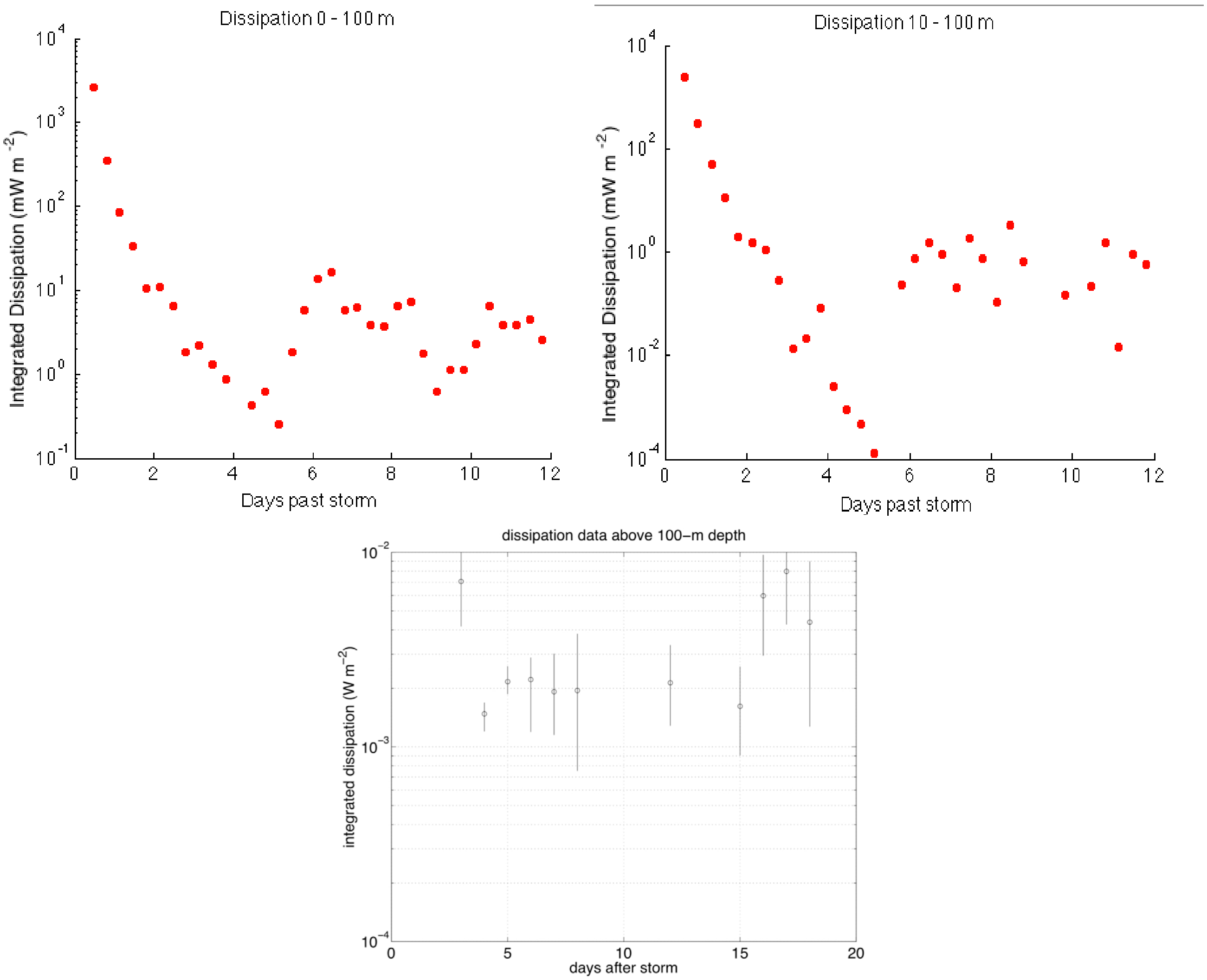

Figure 4. Model simulations of the integrated dissipation (top) and observed integrated dissipation from L. St. Laurent (bottom). Days noted are number of days after September 14.

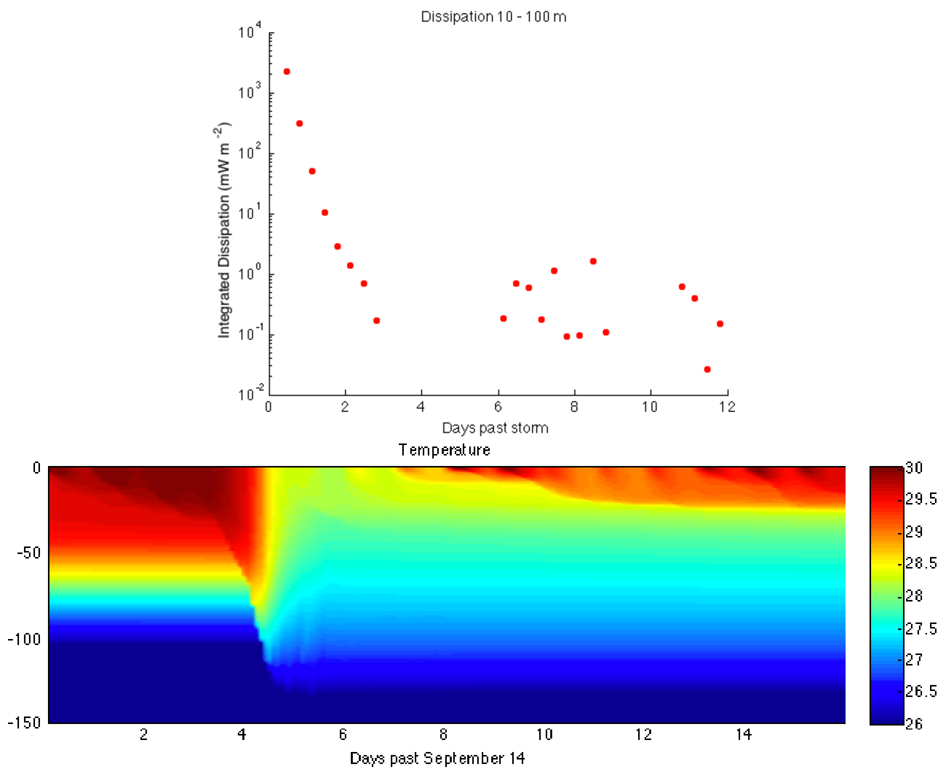

Figure 5. Model simulations of the integrated dissipation (top) and temperature (bottom) for a 50% reduction in heat flux are shown. Days noted are number of days after September 14.

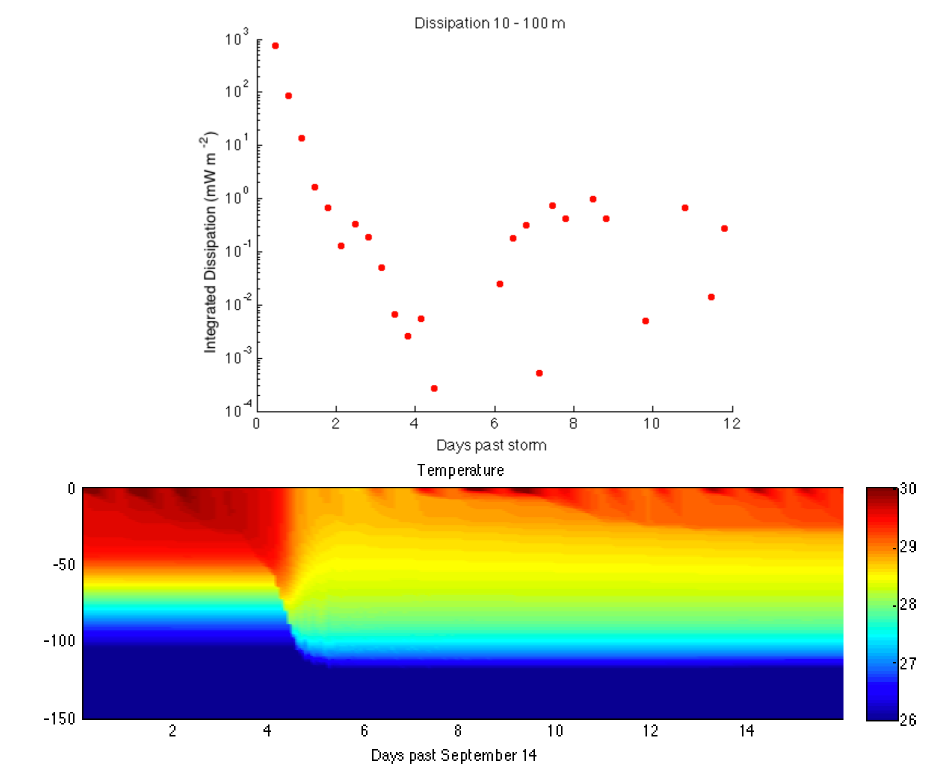

Figure 6. Model simulations of the integrated dissipation (top) and temperature (bottom) for a 50% reduction in momentum flux are shown. Days noted are number of days after September 14.